NONRECIPROCAL CHARACTERISTICS OF BROADSIDE-COUPLED FIN LINES WITH MAGNETIZED FERRITES

Toshihide Kitazawa and Takahiro Sugano

Department of Electrical Engineering
Ibaraki University, Nakanarusawa, Hitachi, 316 Japan

ABSTRACT

A hybrid-mode analytical method is describe to evaluate the nonreciprocal characteristics of various types of the broadside-coupled fin lines with the magnetized ferrite and the finite metallization thickness. Numerical results demonstrate the nonreciprocal properties not only on the phase constants, but also on the characteristic impedances and the conductor losses.

I. INTRODUCTION

Magnetized ferrite is used to realize nonreciprocal devices in microwave and millimeter-wave integrated circuits[1]-[4]. Fin line shows the higher nonreciprocity compared with strip lines[3], but the unilateral fin line with a single-layered ferrite substrate does not exhibit adequate nonreciprocity, and multilayered structures, such as spacers or overlays[2],[3], and broadside-coupled structures, such as tuning septum and floating conductors, can be advantageously utilized to increase the nonreciprocity. Highly accurate and efficient hybrid-mode analysis is indispensable for the nonreciprocal circuit design taking the anisotropy of the magnetized ferrite and the effect of the finite thickness of metallization into consideration. There have been several analysis techniques applicable to the nonreciprocal transmission lines[1] -[4], but mostly coplanar-type structures are treated.

The purpose of this paper is to develop the hybrid-mode formulation procedure for the broadside-coupled fin lines with magnetized ferrites, and to present the nonreciprocal characteristics of not only the phase constants but also the characteristic impedances and the attenuation due to the imperfect conductors.

II. THEORY

Fig.1 shows examples of the broadside-coupled fin lines. When the ferrite layer is magnetized in the x direction, the permeability tensor of the layer is expressed as[1]-[4]

$$\bar{\bar{\mu}} = \mu_0 \begin{bmatrix} 1 & 0 & 0 \\ 0 & \mu_r & j\kappa \\ 0 & -j\kappa & \mu_r \end{bmatrix} \qquad (1),$$

where μ_r and κ are dependent on the operating frequency ω, the applied dc magnetic field H_0, and magnetization of the ferrite $4\pi M_s$,

$$\mu_r = 1 - \frac{\gamma^2 H_0 4\pi M_s}{\omega^2 - (\gamma H_0)^2}, \qquad \kappa = \frac{\gamma\, 4\pi M_s \omega}{\omega^2 - (\gamma H_0)^2} \qquad (2).$$

Full wave analysis is developed based on the extended spectral domain approach (ESDA)[3]-[5]. In this approach, the source fields are introduced in the upper and lower surfaces of the aperture region e_i^u and e_i^l (Fig.2), and the electromagnetic fields in each region can be expressed in terms of the aperture fields[3]-[5]. Transformed Green's functions, which relate the

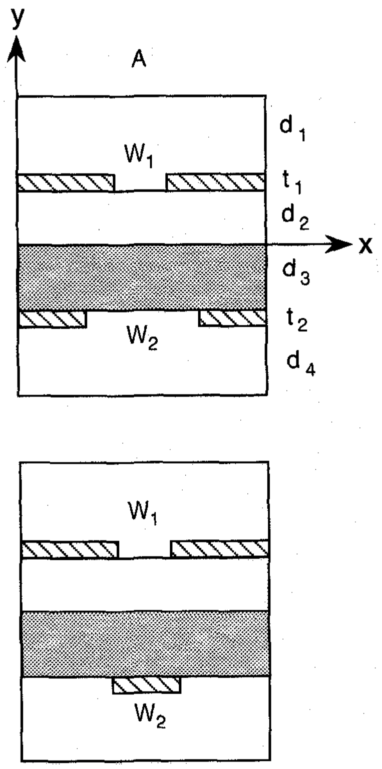

Fig.1 Fin lines with magnetized ferrites

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fields and the aperture (source) fields, are derived with the help of the equivalent circuits in the y-directions. Fig.3 shows the equivalent circuits corresponding to the aperture region of Fig.2.

Finally, by enforcing the continuities of the magnetic fields at the aperture surfaces, we obtain the integral equations for the aperture fields $e_i^U(x)$, $e_i^L(x)$ and implicitly the phase constant β. The determinantal equation for the phase constant β is obtained by applying Galerkin's procedure to the integral equations.

The unknown source (aperture) fields $e^U(x)$, $e^L(x)$ are expanded in terms of the appropriate basis functions :

$$e_{xi}(x) = \left[1-\left\{\frac{2(x-c)}{W}\right\}^2\right]^{-\frac{1}{3}} C_{2i}^{1/6}\left\{\frac{2(x-c)}{W}\right\}$$
$$e_{zi}(x) = \left[1-\left\{\frac{2(x-c)}{W}\right\}^2\right]^{\frac{2}{3}} C_{2i-1}^{7/6}\left\{\frac{2(x-c)}{W}\right\} \quad (3)$$

where $C_k^{\mu}(x)$ are Gegenbauer polynomials, and W, c represent the width and center of the aperture surface. These basis functions represent the singularities of the fields near the conductor edge of the finite metallization thickness case more properly than the conventional basis functions for the zero metallization case (Fig.4).

The frequency-dependent characteristic impedances are evaluated by using the power-voltage basis.

The attenuation due to the imperfect conductor is evaluated by

$$\alpha_c = \frac{P_C}{2 P_0} \quad (4),$$

where P_c is the power lost in the conductors, and it is calculated by the integral of the power dissipation $\sigma|E|^2$ over the region occupied by the conductor S_c

$$P_C = \frac{1}{2}\int_{S_c} \sigma|E|^2 \, dS \quad (5),$$

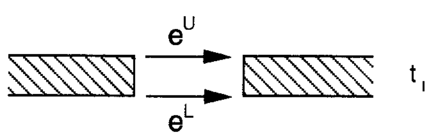

Fig.2 Source fields (Aperture fields)

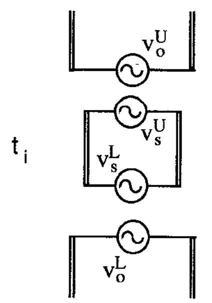

Fig.3 Equivalent circuits of aperture region

where **E** is the electric field inside conductors of the finite metallization thickness.

Eq.(4) with (5) is applicable to the the lines with thicker as well as thinner conductors whose thickness is comparable or less than the skin depth and the attenuation become more significant.

III. NUMERICAL RESULTS

The nonreciprocal phase constants have been reported mainly for the simplest structure of unilateral fin line. The limiting case of the bilateral fin line, i.e., the tuning septum shrinking to zero (W_1 or W_2 -> A) , is reduced to the simple unilateral fin line case. The values of this special case are compared with available data[1] in Fig.5, and good agreement

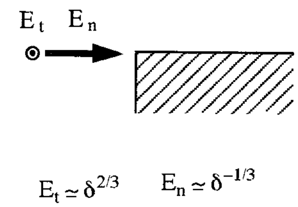

Fig.4 Edge singularities of electric fields

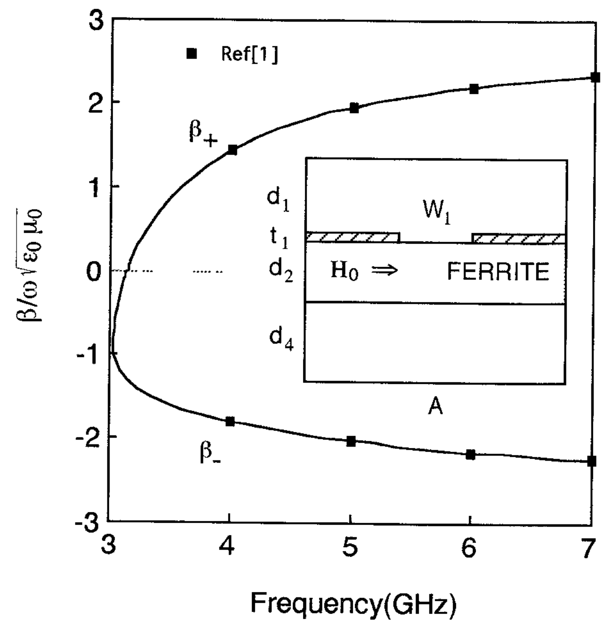

Fig.5 Nonreciprocal characteristics of the unilateral fin line with single-layered ferrite

conductor ; $t_1 = 0$

ferrite; $\varepsilon_F = 13.4$, $M_S =$ 1 42 kA/cm , $H_0 =$ 0.318 kA/cm , $d_2 = 2$ mm

A = 20 mm , $W_1 = 2$ mm , $W_2 = A$

$d_1 = 6$ mm $d_4 = 10$ mm

with the published data is obtained over the frequencies, which shows the validity of the method.

Fig.6(a) shows the phase constants for the forward(+z direction) β_+ and backward(-z direction) β_- propagating dominant modes of the bilateral fin line (aperture width W_1,W_2) . The effect of the metallization thickness on the phase constants is not significant for this structure, but the introduction of the finite metallization thickness into the analysis is indispensable to the loss calculations. Fig.6(b) shows the frequency dependence of the attenuation constants, and it reveals the significant nonreciprocal and the metallization thickness effects. Fig.6(c) shows the frequency dependence of the characteristic impedance calculated based on the power-voltage basis Z_{pv}. The metallization thickness effects on Z_{pv} is not significant, but strong nonreciprocity is observed, and the effect should be taken into consideration for the impedance matching.

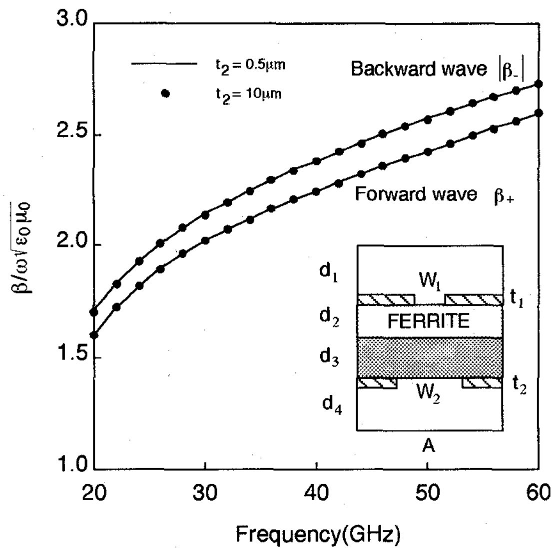

Fig.6 (a) Nonreciprocal phase constants

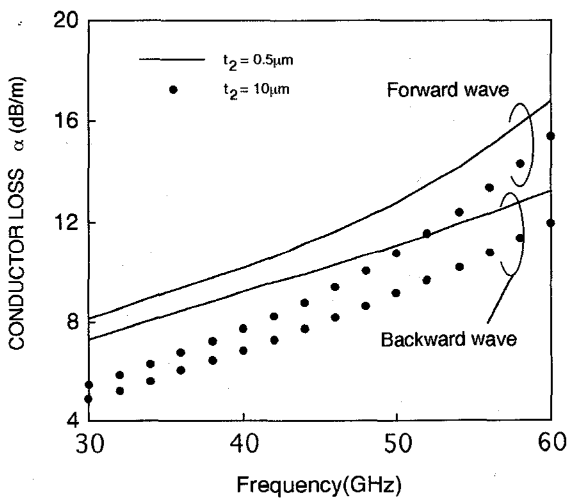

Fig.6 (b) Nonreciprocal attenuation constants

Fig.7 shows the numerical results for the fin line with the floating conductor strip W_2. The thinner ($t_2 = 0.50\mu m$) and thicker ($t_2 = 10\mu m$) strip is considered, whereas the thickness of the fin is fixed as $t_1 = 10\mu m$. The attenuation constant α is affected by the floating conductor and also strong nonreciprocity of α is observed.

IV. CONCLUSIONS

A hybrid-mode analytical method is describe to evaluate the nonreciprocal characteristics of the general structure of the broadside-coupled fin line with the magnetized ferrite. The formulation procedure is based on the extended spectral domain approach (ESDA), and the basis functions used in the computations represent the actual field variations properly near the edge of the conductor of finite thickness. Numerical results demonstrate the nonreciprocal properties on the phase constants, the characteristic impedances and the conductor losses of the broadside-coupled fin lines with the finite metallization thickness.

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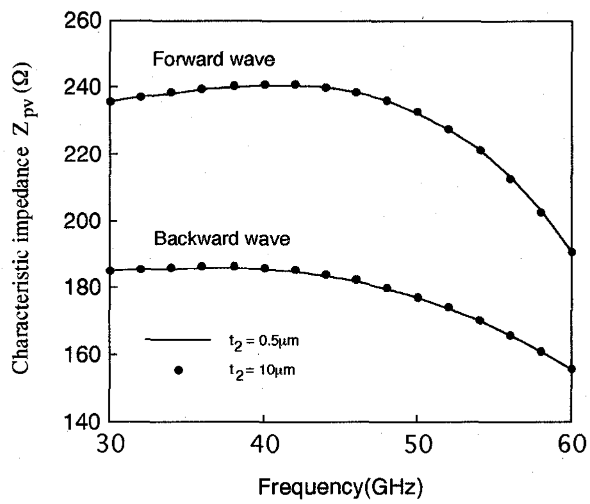

Fig.6 (c) Nonreciprocal characteristic impedances

Fig.6 Nonreciprocal characteristics of the bilateral fin line
conductor ; $t_1 = 10\ \mu m$
ferrite; $\varepsilon_F = 12.5$, $4\pi M_s = 5000$ G ,
$H_0 = 500$ Oe , $d_2 = 0.25$ mm
dielectric; $\varepsilon_D = 12.5$, $d_3 = 0.25$ mm
A = 2.35 mm , $W_1 = 1$ mm , $W_2 = 1.6$ mm ,
$d_1 = d_4 = 2.1$ mm

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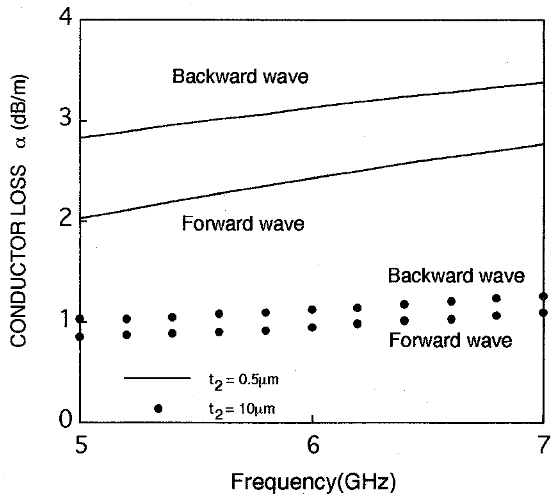

Fig.7 (b) Nonreciprocal attenuation constants

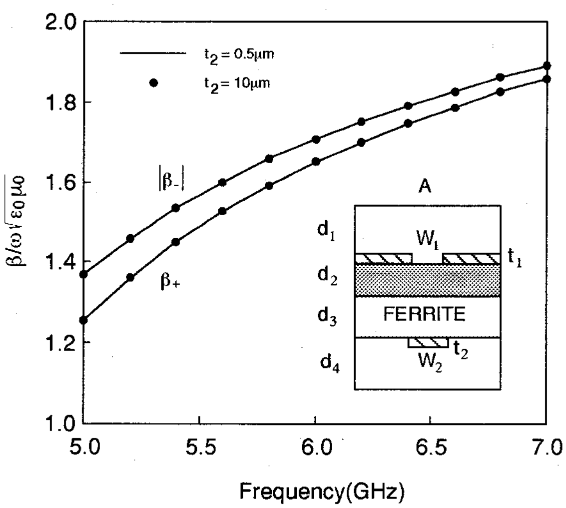

Fig.7 (a) Nonreciprocal phase constants

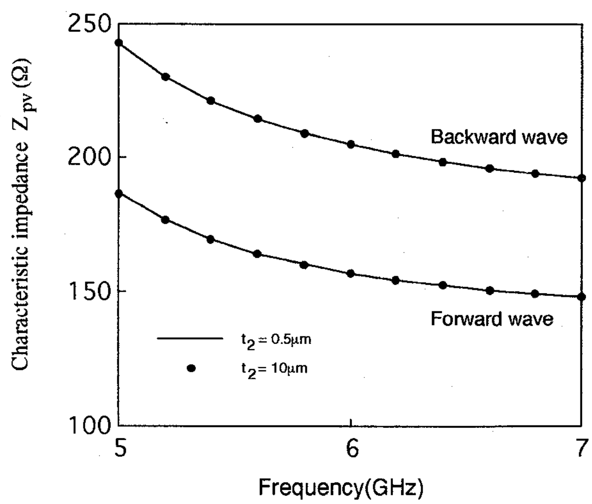

Fig.7 (c) Nonreciprocal characteristic impedances

Fig.7 Nonreciprocal characteristics of the fin line with floating conductor

conductor; $t_1 = 10\ \mu m$
dielectric; $\varepsilon_D = 12$, $d_2 = 0.2$ mm
ferrite; $\varepsilon_F = 13.4$, $M_s = 1.42$ kA/cm,
$H_0 = 0.318$ kA/cm, $d_3 = 1$ mm
$A = 10$ mm, $W_1 = 2$ mm, $W_2 = 0.6$ mm,
$d_1 = 4$ mm, $d_4 = 6$ mm